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A Sediment Quality Triad:

Measures of Sediment Contamination, Toxicity and Infaunal Community Composition in Puget Sound

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Increasing emphasis is being placed upon chemical analyses of sediments to determine the distribution and concentration of toxic chemicals in marine and aquatic environments. The resulting data are often used to characterize chemical accumulations, including delineation of 'hotspots'. These data alone, however, provide no information regarding the possible biological significance of these accumulations. Direct biological testing is needed. the use of a Sediment Quality Triad (chemical, bioassay and infauna) of measurements is advocated here by the authors. The purpose of this study was to determine the correspondence among measures of the three components of the Triad, using available data from several studies of Puget Sound. Good overall correspondence among the three components of the Triad was observed, based upon a comparison of average values from urban and rural portions of the Sound. However, based upon comparisons of data on a station-by-station basis the chemical data alone were not always reliable indicators (and, therefore, predictors) of biological effects. Hence, the importance and usefulness of the Triad was substantiated.

The determination of regional trends in sediment quality is necessary to identify and delineate those areas that are excessively contaminated with toxic chemicals and, therefore, most in need of remedial actions. Sediment deposition zones accumulate and integrate toxic chemical inputs from multiple nearby sources over time; chemical data from analyses of samples from these zones can be very helpful in determining the history of accumulation of inputs and geographic trends in degrees of contamination Assessments of sediment quality have often involved the acquisition of only sediment chemistry data. However, these chemical data alone provide limited or no evidence of the biological damage that may be occurring due to the contamination. That is, no answer to the biological 'So what?' question is provided.

Chapman & Long (1983) argued that modern assessments of sediment quality must involve at least three categories of measurements: (1) concentrations of toxic chemicals, (2) toxicity of environmental samples, and (3) evidence of modified resident biota, preferably the infauna. Together, these three categories of measurements constitute our 'Sediment Quality Triad'. We believe that strong evidence of a biologically damaging excess of toxic chemicals to sediments is provided by the Sediment Quality Triad. Bulk chemical measures alone provide no indication of biological damage, but are needed to determine the degree and nature of contamination. They are also useful in providing clues regarding possible sources. Direct testing provided through bioassays can establish the toxicological significance of chemistry data. However, since bioassays are usually performed in a laboratory environment, they may not accurately mimic the conditions under which resident biota may be exposed to the toxic chemicals. Measures of changes in resident biota exposed to or living in the sediments are needed, at least initially while the technology of sediment bioassays is under development, to corroborate the laboratory bioassay data. Community composition changes alone, however, may provide misleading evidence of *in situ* toxic chemical effects, since benthic communities may be overwhelmingly modified by recruitment cycles, predation, competition, natural events, and subtle non-pollution related variations in the environmental properties of the sediments or overlying water.

The Triad is offered here as one approach or concept applicable to development of a sediment quality index. Our overall long-range intent is to develop such an index. The purpose of this paper is to report the first step in the development of that index: a review of existing data from Puget Sound to determine the correspondence among sediment contamination, toxicity and infauna data. This initial low-cost step was taken to allow evaluation of the usefulness of proceeding with a subsequent step: a full field trial of the Triad.

Puget Sound is an inland marine system located in northwestern Washington. Because of its relatively pristine condition, Puget Sound remains as a very important resource for fisheries and recreation to the over 2.3 million people inhabiting the surrounding region. Industrial activities bordering the Sound include the aerospace maritime, ship-building, wood products and petrochemical industries. Relatively high concentrations of toxic chemicals have been found in sediments from parts of those bays bordering the Sound where most urban/industrial growth has occurred (Long, 1982, 1983; Malins *et al.*, 1984). The deep portions of the Sound and the remote, rural bays are relatively contaminant-free.

Methods

Approach

The overall approach taken in this study was to compare measurements of sediment chemistry, toxicity and infauna by acquiring available, compatible data from a variety of sources. The data set reviewed and presented here is a compilation of subsets of data gathered by the U.S. Environmental Protection Agency (EPA), the National Marine Fisheries Service (NMFS), the Municipality of Metropolitan Seattle (Seattle METRO) and the authors, in their respective efforts to characterize geographic trends in sediment quality. The investigators, station locations, and sediment characteristics are listed in Table 1.

Bioassays were performed by the second author with samples collected in 1981 at stations previously (1979, 1980) sampled for chemistry and infauna analyses by NMFS (Malins *et al.*, 1980, 1982) with the exception of Case Inlet. Bioassays of Case Inlet samples were performed by EPA in 1983 (Joseph Cummins, EPA, unpublished data). Swartz *et al.* (1982) performed chemistry and infauna analyses and bioassays on samples collected in 1981 by EPA. Comiskey *et al.* (1984) reported all three measures on samples collected in 1982/83 for METRO; the second author performed the bioassays.

Subsets of the data from these organizations were chosen based upon: (1) the narrowest possible range of sediment texture (mean grain size 5.8–8.5 Phi), sand:mud ratio (0.02–0.23) and depth (7–60 m); and (2) availability of all three measures of the Triad. One station in Samish Bay (No. 11), for which taxonomic analyses were conducted prior to sediment analyses, was an exception with a mean grain size of 2.8 Phi and a sand:mud ratio of 3.69 (Table 1). Despite this difference

TABLE 1

Station locations, numbers and characteristics from investigations summarized in this report.

Location	Station numbers		Mean grain size (Phi)	Sand:mud ratio	Depth (m)
	Chapman *et al.*, 1982 (bioassays)	Malins *et al.*, 1980 (chemistry, infauna)			
Elliott Bay					
Piers 54/56[a]	12	10015[d]	7.0	0.12	20–60
Duwamish					
W. Waterway[a]	20	10038	7.1	0.22	15–20
E. Waterway[a]	25	10039	8.5	0.04	12–16
S. Harbor Is.[a]	29	10031	7.1	0.18	10–20
Commencement Bay					
Inner Bay[a]	40	09033	6.0	0.16	20–50
Hylebos Waterway[a]	48	09027	6.9	0.03	10–12
City Waterway[a]	67	09031	6.7	0.08	7–11
Sinclair Inlet					
Inner[b]	76	08004	—	0.02	8–10
Outer[a]	81	08005	—	0.03	10–12
Case Inlet[a]	—	12062	7.4	0.06	20–45
	Chapman *et al.*, 1984 (bioassays, infauna)	EPA, Region X (unpublished data) (chemistry)			
Samish Bay					
A[c]	11	—	2.8	3.69	14
B[c]	12	—	6.0	0.10	15
	Swartz *et al.*, 1982 (chemistry, infauna, bioassays)				
Commencement Bay					
Hylebos Waterway		A9	7.0	0.15	13.0
Hylebos Waterway		A10	6.4	0.22	13.0
Hylebos Waterway		H1	7.3	0.06	13.0
Blair Waterway		A6	6.4	0.18	18.0
Blair Waterway		L1	6.3	0.12	16.0
Sitcum Waterway		S1	6.1	0.12	15.0
City Waterway		C11	6.0	0.23	9.0
	Comiskey *et al.*, 1984 (chemistry, infauna, bioassays)				
Elliott Bay					
off the		1406	5.8	0.23	19.3
Denny Way		1512	6.6	0.11	40.0
Combined sewer		1606	5.6	0.23	30.1
Overflow		1612	5.8	0.20	39.9

[a] Six samples quarterly in 1979: sampling by NMFS; taxonomy identification by E.V.S. Consultants; bioassays in 1983 by EPA.
[b] Six samples taken in three quarters in 1979 (not in February); sampling by NMFS, taxonomic identifications by E.V.S. Consultants.
[c] Four samples taken once in 1983; sampling and taxonomic identifications by E.V.S. Consultants.
[d] Benthos (less than 1 mm) not present in February 1979.

in sediment texture, the infauna were indistinguishable from those at the adjacent station (No. 12). Therefore, the data from this station were not excluded from subsequent analyses because of the need for information from the relatively scarce reference stations. Original station numbers used by the respective investigators are retained and used here.

Sampling stations (Fig. 1 and 2) that met the criteria above were chosen from five of the embayments that border Puget Sound: (1) Elliott Bay and the industrialized Lower Duwamish Waterway near Seattle; (2) Commencement Bay and its industrial waterways near Tacoma; (3) Sinclair Inlet near Bremerton; (4) Samish Bay; and (5) Case Inlet. The latter two bays are rural and relatively isolated from large municipal/industrial centres. They are used here as reference areas.

All sediment samples were collected with a 0.1 m Van Veen grab modified with flaps to allow access to surficial sediments through the top of the grab. A minimum sediment depth of 6 cm was sampled.

Chemical Analyses

NMFS samples were analysed for organic compounds by solvent extraction with methanol/dichloromethane, column chromatography and capillary column gas chromatography with mass spectrometry, flame ionization and electron capture detectors. Samples for metal analyses were digested in hot acid and analysed either by atomic absorption spectrophotometry or by inductively coupled argon plasma emission spectroscopy (Malins *et al.*, 1984).

Seattle METRO performed analyses for organic compounds by a similar solvent extraction, mild distillation, high pressure liquid chromatographic separations and high resolution gas chromatography/mass spectrometry. Trace metals were analysed by a nitric acid/peroxide digestion followed by either graphite furnace, X-ray fluorescence, neutron activation, anodic stripping or cold vapour analytical techniques. The copper, lead and zinc data reported below were determined by X-ray fluorescence (Romberg *et al.*, 1984).

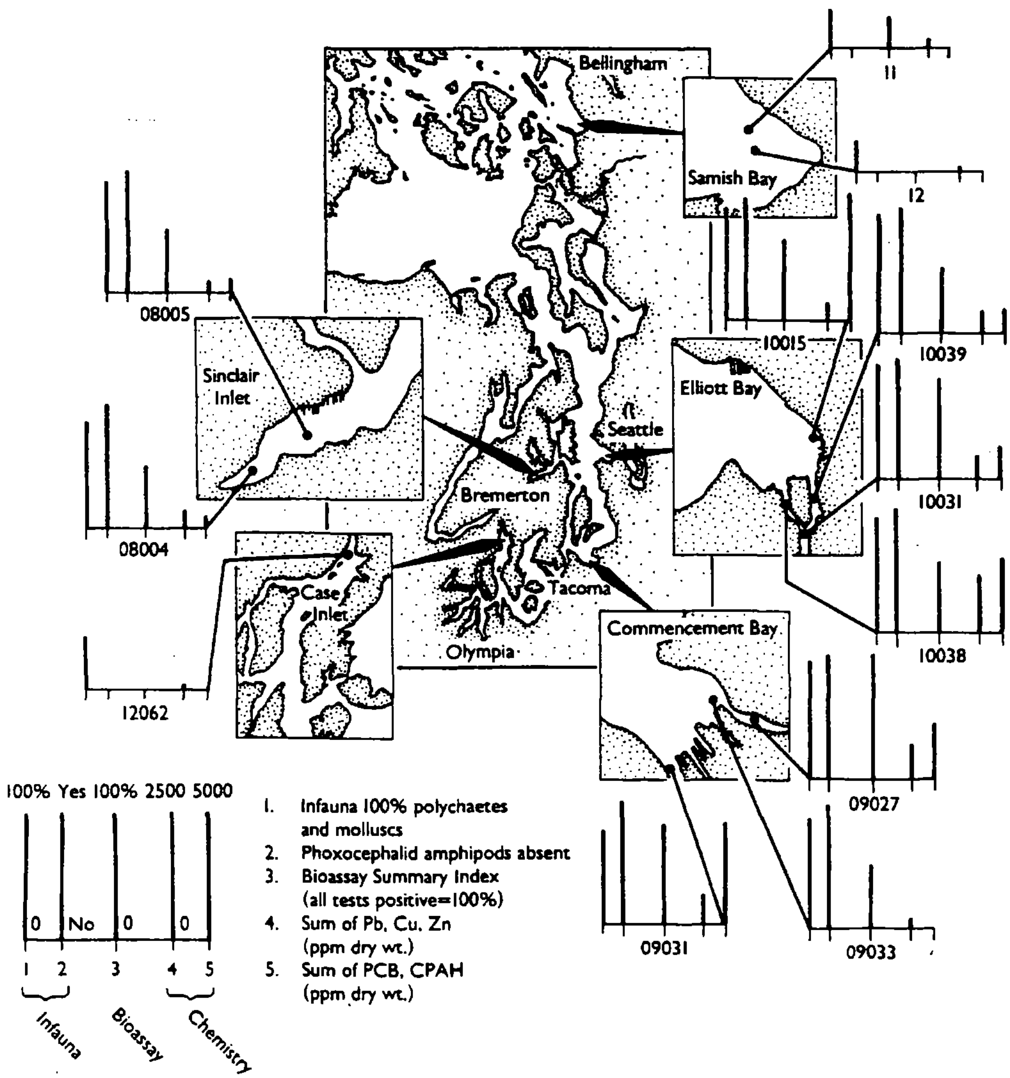

Fig. 1 Correspondence among Triad of Sediment Quality measurements for samples from Samish Bay, Elliott Bay, Commencement Bay, Case Inlet and Sinclair Inlet. Data are from Tables 2, 3 and 4.

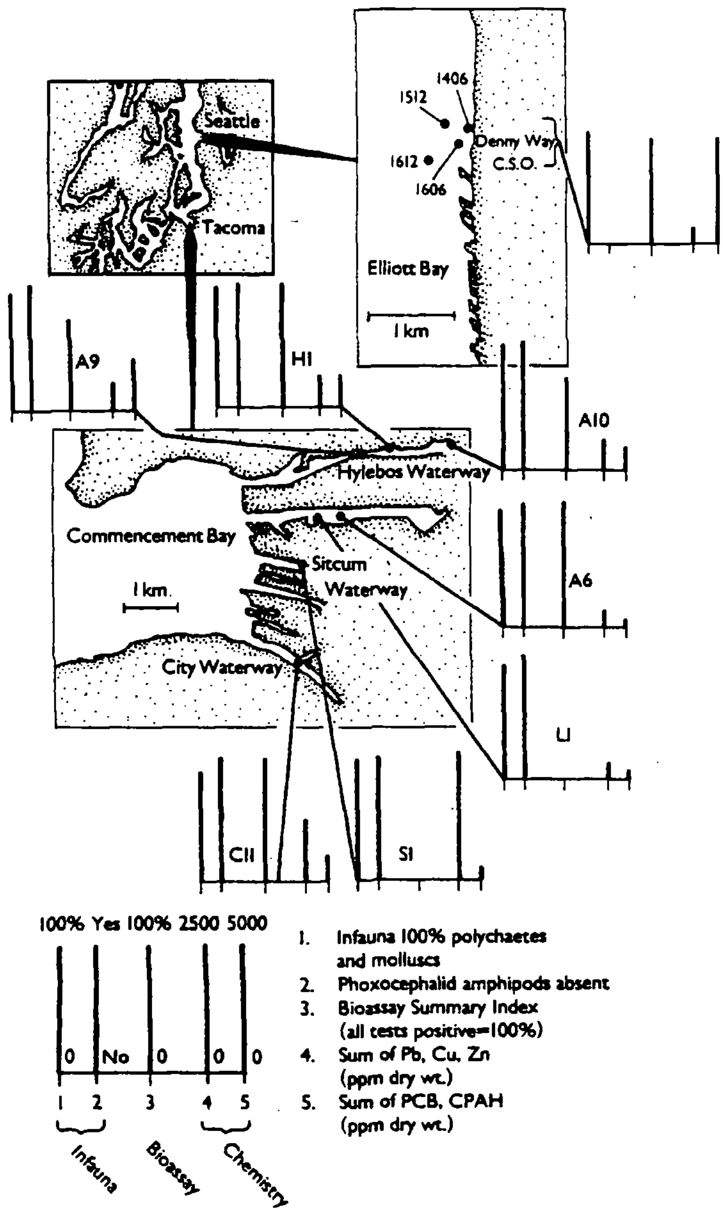

Fig. 2 Correspondence among Triad of Sediment Quality measurements for samples from Commencement Bay waterways and Elliott Bay. Data are from Tables 2, 3 and 4.

EPA analyses of Samish Bay sediments were performed with methods similar to those used by Seattle METRO (Joe Blazevich, EPA, personal communication). The analyses by EPA of the Commencement Bay samples were performed with slightly different methods (Schultz *et al.*, 1983). The organic analyses were performed by extraction with anhydrous sodium sulphate and acetonitrile, column chromatography with mass spectrometry, flame ionization and electron capture detectors. Trace metals were analysed by nitric acid/hydrochloric acid digestion followed by atomic absorption spectrophotometry.

The chemical data for the Triad are presented as sums of three trace metals (lead, copper and zinc), PCBs (polychlorinated biphenyls) and CPAHs (combustion polynuclear aromatic hydrocarbons). These particular chemicals were selected as representative of a much broader suite that was analysed. They are the chemicals for which the analytical results were judged by the authors to be compatible among laboratories.

Sediment Bioassays

A wide variety of bioassays have been developed and applied in Puget Sound (Chapman *et al.*, 1984a). They have included those tests reported below: lethality to the amphipod *Rhepoxynius abronius*; alterations in the respiration rate of the oligochaete *Monopylephorus cuticulatus*; abnormal development of the larvae of the oyster *Crassostrea gigas*; mutagenicity and cytotoxicity among cultured gonad cells of rainbow trout (*Salmo gairdnerii*); development and survival of the larvae of the polychaete *Capitella capitata*; and development of larvae of the surf smelt *Hypomesus pretiosus pretiosus*.

Bulk sediments were used in the tests with *Rhepoxy-*

nius, *Capitella* and *Hypomesus*. Elutriates were tested in the *Monopylephorus* and *Crassostrea* bioassays. Bioassays with trout cells were performed with the material extracted from sediments in iterative dichloromethane/methanol and DMSO solvent extractions.

Amphipod lethality bioassays indicated toxicity when mean survival was significantly less ($p = 0.05$) than controls for replicated tests or a survival value of 70% or less was observed for unreplicated tests (Swartz *et al.*, 1982). Oligochaete respiration testing indicated toxicity when mean respiration rate was significantly different ($p = 0.05$) than controls (Chapman *et al.*, 1982). Oyster larvae tests indicated toxicity when mean abnormality counts were greater than 20% (Chapman & Morgan, 1983). Fish cell tests indicated toxicity when significantly more ($p = 0.05$) mitotic abnormalities were detected in test exposures compared to controls (Kocan *et al.*, 1982). Polychaete life-cycle tests indicated toxicity when abnormal larvae were induced, survival and/or growth were significantly reduced ($p = 0.05$) compared to control values (Chapman & Fink, 1984). Surf smelt partial life-cycle tests indicated toxicity when premature hatching occurred, survival of eggs and/or larvae was significantly reduced ($p = 0.05$) compared to control values (Chapman *et al.*, 1983).

All available sediment bioassay data were pooled to obtain a 'Bioassay Summary Index' value to apply to the Triad, assuming that the significance of each type of bioassay test was equal. This index value was a dimensionless number, expressing the percent of the types of tests that were significantly toxic per site based upon the criteria given above. For example, four tests were positive out of six attempted with samples from station 10015 in Elliott Bay; the index value is 0.67, or 66.6% of the tests.

Sediment collections for Infauna Analyses

All investigators used basically similar sample collecting methods with some slight variations in sample handling. Modified Van Veen (0.1 m^2) grabs were used for collection of all sediments.

NMFS subsampled the material in the grab. Two core samples each with a surface area of 100 cm^2 and a depth of 10 cm were taken from each grab for infaunal analyses. Three grab samples were taken at each station. The resulting six subsamples were pooled for analyses. Sediment from the 1000 cm^3 core samples was wet-sieved through 1 mm mesh stainless steel sieves and the material that remained was preserved and analysed for infauna. Collections were undertaken quarterly during 1979 and twice during 1980.

Samples from Samish Bay were collected in May 1983 by the second author using the same Van Veen grab. Two grab samples were taken at each station. Two 1000 m^3 cores were taken from each grab using the NMFS core sampler and treated as above resulting in four subsamples pooled for analyses.

Seattle METRO retained material (no subcoring) on a 1 mm mesh sieve for taxonomic identifications. Samples were taken in the summer of 1982.

EPA used the same methods employed by Seattle METRO. Sampling was conducted in the spring of 1981.

Taxonomic Analyses

The second author conducted identifications of infauna in the samples collected by NMFS along with the samples from Samish Bay. Identifications of infauna in the Seattle METRO samples was performed by the University of Washington (Comiskey *et al.*, 1984). EPA performed their own taxonomic analyses in-house (Dr. Rick Swartz, EPA, personal communication). All three laboratories sorted organisms into major phylogenetic groups and then performed identifications to the lowest possible taxonomic level currently attainable. Though some informal interlaboratory taxonomic comparisons have been performed, no rigorous experiments to ensure compatibility of data among them have been conducted for all species. Therefore, the data are generally reviewed below by major groups, not at the species level. Those family and species level identifications mentioned below represent compatible data for all laboratories.

The infauna data for the Triad are presented in terms of the combined percent abundance of polychaetes and molluscs, and the presence or absence of sensitive phoxocephalid amphipods. Areas with large waste inputs or residues are typically characterized by a dominance of polychaetes and molluscs and an absence or low abundance of other groups (Pearson & Rosenberg, 1978). Urban embayments such as Bellingham Bay in Puget Sound are characterized by an infaunal composition, on average, of up to 86% polychaetes and molluscs (Benedict *et al.*, 1984). In the New York Bight, polychaetes and molluscs comprise an average of 95% of the benthic infauna (Caracciolo & Steimle, 1983). Four polychaete families dominant in urban embayments in the present study (Lumbrineridae, Spionidae, Cirratulidae and Capitellidae) are commonly found in grossly polluted areas (Gray, 1982; Chapman, in press).

In contrast, sensitive amphipods are generally excluded from these areas. Caracciolo & Steimle (1983) noted that amphipods in the New York Bight are generally intolerant of pollutants and are virtually absent from polluted areas. Phoxocephalid amphipods are particularly sensitive. Swartz *et al.* (1981, 1982) found that phoxocephalid amphipods were absent from areas in Puget Sound and the Southern California Bight where high levels of sediment toxicity were recorded. Oakden *et al.* (1984) have shown that phoxocephalids exhibit a behavioural avoidance of contaminated sediments.

Results

Chemistry

Data for trace metals and selected organic compounds are given in Table 2. Because of inconsistencies in the number of aromatic hydrocarbons quantified by the various laboratories, judicial use is made of a correction factor to normalize the CPAH data (see explanatory footnote in Table 2). Samples from rural reference areas had low or non-detectable concentrations of trace metals and organics, whereas those from the urban bays had considerably elevated levels. Metals were most concentrated in samples from the following highly industrialized areas: the Duwamish Waterway near Seattle and the City, Sitcum and Hylebos Waterways near Tacoma.

TABLE 2

Summary of sediment chemistry data for all stations. Data from investigators identified in Table 1.

		Metals[a]				Organics		
Area	Station	Pb	Cu	Zn	ΣPb, Cu, Zn	PCB[b]	CPAH[c]	Ō[d] = (ΣPCB + CPAH/10)
Samish Bay	11	10	15	41	66	<100	N.D.[g]	N.D.
	12	46	42	93	181	<100	N.D.	N.D.
Case Inlet	12062	24	45	83	152	4	480	52
Elliott Bay	10015	111	91	133	335	492	46500	5142
	10038	627	206	319	1152	665	25000	3165
	10031	265	131	204	600	533	7710	1304
	10039	160	109	175	444	338	3880	726
	1406	89, 2109	130, 87	140, 170	413	1930	34520[f]	5392
	1512	54, 94	52, 55	100, 110	233 $\bar{x}$=4104	1416	19947	3411 $\bar{x}$=4104
	1606	88, 49	57, 34	150, 86	232	2823	4945	3318
	1612	90, 98	62, 54	120, 110	267	1112	31938	4306
Commencement Bay	09027	154	259	324	737	1150	12530	2403
	09031	269	178	224	671	383	38830	4266
	09033	28	51	57	136	N.D.	500	50
	A9	147	179	202	528	1329	3850[h] (6417)	1971
	A10	123	173	259	555	Trace	4871[h] (8118)	812
	H1	197	211	334	742	390	6120[h] (10200)	1410
	L1	74	106	132	312	N.D.	1442[h] (2403)	240
	A6	69	72	132	273	Trace	1055[h] (1758)	176
	S1	791	581	1190	2562	N.D.	2565[h] (4275)	428
	C11	225	276	742	1243	Trace	7005[h] (11675)	1168
Sinclair Inlet	08004	98	151	156	405	176	2690	445
	08005	136	184	238	558	218	1960	414

[a] ppm dry weight.
[b] ppb dry weight, Σ1242, 1254, 1260 or Σ2-CB, 3-CB, 4-CB, 5-CB, 6-CB, 7-CB, 8-CB, 9-CB, 10-CB.
[c] ppb dry weight, = Σ of fluoroanthene, pyrene, benzo(a)anthracene, chrysene, benzofluoranthenes, benzo(e)pyrene, perylene, indeno (1,2,3-CD)pyrene.
[d] Organic average = ΣPCB + ΣCPAH (combustion PAH)/10; division by 10 reduces the CPAH values to approximately equal weight in the sum as the PCBs.
[e] N.D. = below detection limits (70 ppb dry weight for fluoranthene, 400 ppb for indeno (1,2,3-CD)pyrene, and 50 ppb for all others).
[f] Perylene was not reported; since perylene is normally less than 10% of the ΣCPAH, no correction was made.
[g] Two values reported; averaged to form the sum, ΣPb, Cu and Zn.
[h] The CPAHs for these samples only included fluoranthene, pyrene, benzo(a)anthracene and chrysene; based on the average contribution of these four to the other ΣCPAH values in this table (60%), a comparable ΣCPAH value was calculated and used for the summations.
Σ = sum.

Organic compounds were most concentrated in samples from the lower Duwamish, Hylebos and City Waterways and in samples from inner Elliott Bay near both the Denny Way Combined Sewer Overflow and the Pier 54 Combined Sewer Overflow.

Bioassays

The bioassay data are listed in Table 3. The data set encompasses tests of samples from stations listed in Table 1 as well as all available data from samples that met our criteria that were taken in the immediate vicinity (within 100 m) of these stations. Data from these additional samples were included to provide a broad basis for comparisons of results. Notations of positive (toxic) and negative (not significantly toxic) responses are given along with the Bioassay Summary Index. Only one of the bioassay tests performed with a sample from a reference station was positive (the fish cell cytotoxicity test with sample No. 11 from Samish Bay); the remainder were negative. The sample from Case inlet, the other reference area, was tested only with the amphipod bioassay; it was not toxic at this station. Most of the types of bioassays were positive at most stations in the urban bays. Samples from stations in inner Elliott Bay, the lower Duwamish Waterway and the industrial waterways of Commencement Bay were clearly toxic in most types of tests.

Infauna

Percent contributions of various taxa to the total communities of infauna per station are presented in Table 4. The data from the NMFS samples indicated that at stations considered to be impacted by pollution (Elliott Bay, Duwamish Waterway, Sinclair Inlet, Commencement Bay Waterways), the benthic community was composed predominantly of polychaetes and molluscs (73.2–98.4% of totals). Arthropods and echinoderms were generally not an important part of the community at these stations. In addition, members of the pollution-sensitive amphipod family Phoxocephalidae were

TABLE 3
Summary of sediment bioassay data for all stations[a]

Area	Station	Bioassay data[b]						
		Amphipod lethality	Oligochaete respiration	Oyster larvae abnormality	Fish cell effects	Polychaete life-cycle effects	Surf smelt partial life-cycle effects	Bioassay summary index[c]
Samish Bay	11	no	no	no	yes	N.D.	N.D.	0.25
	12	no	no	no	no	N.D.	N.D.	0.00
Case Inlet	12062	no	N.D.	N.D.	N.D.	N.D.	N.D.	0.00*
Elliott Bay	10015	yes	yes	no	yes	no	yes	0.67
	10038	yes	yes	N.D.	no	N.D.	N.D.	0.67
	10031	yes	yes	yes	yes	no	yes	0.83
	10039	N.D.	no	N.D.	yes	N.D.	N.D.	0.50
	1406, 1512, 1606, 1612	yes	yes	N.D.	yes	no	yes	0.80[d]
Commencement Bay	09027	N.D.	yes	N.D.	yes	N.D.	N.D.	1.00
	09031	N.D.	yes	no	yes	yes	yes	0.80
	09033	N.D.	no	N.D.	yes	N.D.	N.D.	0.50
	A9	no	yes	N.D.	yes	N.D.	N.D.	0.67
	H1	yes	yes	N.D.	yes	N.D.	N.D.	1.00
	A10	no	yes	N.D.	yes	N.D.	N.D.	0.67
	L1	no	N.D.	N.D.	N.D.	N.D.	N.D.	0.00*
	A6	yes	N.D.	N.D.	N.D.	N.D.	N.D.	1.00*
	S1	no	N.D.	N.D.	N.D.	N.D.	N.D.	0.00*
	C11	yes	yes	N.D.	yes	N.D.	N.D.	1.00
Sinclair Inlet	08004	N.D.	no	N.D.	yes	N.D.	N.D.	0.50
	08005	N.D.	yes	N.D.	no	N.D.	N.D.	0.50

[a] Data were extracted, as appropriate, from the following sources: Chapman *et al.*, 1982, 1983, 1984b; Chapman & Fink, 1983: Ott *et al.*, 1983; Swartz *et al.*, 1982.
[b] Yes = significant (positive) result; no = non-significant (negative) result; N.D. = no data.
[c] Index values are calculated as the total number of positives over the total number of positive and negative results.
[d] These stations are considered as a group due to their proximity to each other.
* Indicates that values are based on only one measured parameter, and require verification by one or more different bioassay tests.

usually absent from these stations. In contrast, at the reference stations (Case Inlet and Samish Bay), the importance of polychaetes and molluscs in the benthic community dropped dramatically (23.8–47.0% of totals). Echinoderms and arthropods were more abundant, and phoxocephalids were present at the reference stations.

A similar pattern was evident for the METRO Seattle and EPA samples which were all from stations considered polluted. Polychaetes and molluscs comprised the majority of the fauna (85.4–99.2% of totals). Echinoderms and arthropods were generally not an abundant faunal component. Phoxocephalids were present only in very low abundances (0.7% of total) in Elliott Bay.

Sediment Quality Triad

Chemistry, bioassay and infauna data from Tables 2, 3 and 4, respectively, are summarized graphically as five measures in Figs 1 and 2. They are presented as: (1) the percent of the infauna represented by polychaetes and molluscs; (2) presence–absence of phoxocephalid amphipods; (3) the Bioassay Summary Index; (4) sums of three trace metals; and (5) sums of selected organic compounds.

It is apparent from Figs 1 and 2 that samples from those areas that were highly chemically contaminated usually elicited toxic responses in bioassays and generally had demonstrably modified resident infauna (as compared to remote uncontaminated areas). Samples from stations A9, HI, CII, 09027, 09031, 10015, 10031, and 10038 demonstrated high contamination, high toxicity and modified infauna (i.e. dominated by polychaetes and molluscs and lacking in phoxocephalids). The samples from stations 1406, 1512, 1606 and 1612 had a combined 0.7% contribution from phoxocephalids to the infauna, were dominated by polychaetes and molluscs, had a 0.80 Bioassay Summary Index and over 4000 ppm total selected organics. Samples from stations A6, A10, 10039, 09033, 08004 and 08005 had only low to moderate levels of contamination, intermediate to high bioassay responses and relatively highly modified infauna. Samples from stations LI and SI had moderate (LI) to relatively high metals (SI) contamination, a negative bioassay response with only one type of test (amphipod lethality) and modified infauna. Samples from the three reference stations demonstrated low or undetectable contamination, low or no positive bioassay responses, low (23.8 to 47.0%) contribution of polychaetes and molluscs to the infauna and presence of phoxocephalid amphipods.

Discussion

Correspondence Among Triad Measures

Overall, when the data for all sites are pooled for urban areas and rural reference areas, the mean values for all three components of the Triad appear to corre-

TABLE 4

Percent contribution of selected taxa to total infaunal assemblages.

Area:	Elliott Bay	Commencement Bay							Elliott Bay	Duwamish River			Sinclair Inlet		Commencement Bay			Case Inlet		
Location:	Denny Way CSO[a]	Hylebos			Blair		Sitcum	City	Pier 54/56	S.Harbor Is.	W.W'way	E.W'way	inner	outer	Hylebos	City	inner	Reach Is.	Samish Bay	
Station:	1406+1512+ 1606+1612	A9	H1	A10	L1	A6	S1	C11	10015	10031	10038	10039	18004	08005	09027	09031	09033	12062	11	12
Polychaeta	29.5[b]	*88.8*	*92.9*	*63.9*	35.7	49.9	*52.5*	*70.9*	*51.8*	*88.9*	44.9	*53.1*	*71.2*	41.5	*52.0*	30.2	24.2	41.3	27.2	21.8
Lumbrineridae	2.7	7.5	5.7	5.8	3.2	5.1	0	<0.1	5.2	8.1	20.2	13.7	1.7	11.5	11.5	1.7	3.0	3.0	2.4	4.1
Spionidae	1.8	0.8	0.4	0.8	1.0	1.6	0.7	14.9	3.1	0.3	1.0	0.4	9.5	6.5	1.5	5.9	1.0	13.4	1.2	1.2
Cirratulidae	1.5	*77.9*	*79.9*	*50.4*	23.5	17.7	40.4	15.0	0.8	*65.8*	11.3	34.6	*51.2*	11.3	24.0	1.6	3.4	0.2	0	0.8
Capitellidae	4.3	0.2	0.2	0.4	1.8	1.5	0.7	1.4	20.2	3.6	12.2	2.4	0.3	0.3	3.3	7.0	6.4	9.5	0.4	0
Maldanidae	2.5	0.4	< 0.1	0.4	1.6	8.7	< 0.1	0	1.0	0	0	0.4	0	1.2	0.5	1.3	5.8	0	0.8	1.6
Others	16.7	2.0	6.6	6.1	4.6	15.3	10.6	39.5	21.5	11.1	0.2	1.6	8.5	10.7	11.2	12.7	4.6	15.2	22.4	14.1
Mollusca	*54.8*	8.1	6.3	35.4	*58.2*	43.6	45.8	21.9	42.9	6.4	49.9	45.3	19.2	43.5	41.8	43.0	*65.3*	5.7	2.0	2.0
Axinopsida serricata	33.3	1.2	3.0	34.7	*51.7*	36.0	23.5	0.4	31.4	3.8	32.3	30.2	3.8	21.5	32.1	22.6	37.2	1.5	0.4	0
Macoma carlottensis	13.8	0	0	0	0	0	0	0	5.8	2.0	11.5	14.5	0.9	1.6	0.5	14.2	24.4	0.9	0	0
Macoma nasuta	0	0.6	1.0	0.8	2.1	3.3	16.5	5.8	0	0	0	0	0	0	0.3	1.5	0	0.5	0	0
Others	7.7	6.3	2.3	0.1	4.4	4.3	5.8	15.7	5.7	0.6	6.1	0.6	14.5	20.4	8.9	4.7	3.7	2.8	1.6	2.0
Polychaeta and Mollusca	*84.4*	*96.9*	*99.2*	*99.3*	*93.9*	*93.5*	*98.3*	*92.8*	*94.7*	95.2	*94.8*	*98.4*	*90.4*	*85.0*	*93.8*	*73.2*	*89.5*	47.0	29.2	23.8
Echinodermata	< 0.1	0	< 0.1	0	0.2	1.2	0.2	0	0	0	0	0	0	0.5	0	0.3	1.4	44.6	12.6	12.3
Arthropoda	15.2	3.1	0.8	0.7	5.0	5.5	1.3	7.0	2.1	4.4	4.8	1.4	9.1	14.5	6.1	26.9	8.8	4.0	*57.3*	*63.1*
Phoxocephalidae	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	7.3	4.9
Lysianassidae	0	0.2	< 0.1	0	< 0.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4
Others	14.5	2.9	0.7	0.7	4.9	5.5	1.3	7.0	2.1	4.4	4.8	1.4	9.1	14.5	6.1	26.9	8.8	3.1	49.6	57.8

[a] Mean of the four stations.

[b] Mean percent occurrence; values greater than 50% are italicised.

TABLE 5
Summary data for Sediment Quality Triad (overall means calculated, respectively, from data in Tables 2, 3 and 4).

	Reference areas[a]	Urban areas[b]
Chemistry		
Sum of Pb, Cu, Zn	133 ppm	679 ppm
Sum of PCBs, selected CPAHs	N.D.[c]-52 ppm	1660 ppm
Bioassay		
Bioassay Summary Index[d]	0.12	0.72
Infauna		
percent contribution of polychaetes and molluscs	33.0%	92.5%
percent contribution of phoxocephalids	4.4%	0.04%
percent contribution of total arthropods	41.5%	6.9%
percent contribution of total echinoderms	23.2%	0.2%

[a] Samish Bay, Case Inlet.
[b] Elliott Bay, Commencement Bay, Sinclair Inlet.
[c] N.D. = Not detected.
[d] Calculated with results from stations with two or more tests performed.

spond with each other relatively well (Table 5). That is, based upon these means, the sediments from urban areas appear to be highly contaminated, highly toxic in most types of tests and inhabited by mainly polychaetes and molluscs as compared to sediments from reference areas.

The good correspondence among measures initially suggests that any one of the three Triad components suffices to determine pollution status. However, this correspondence between measures is not nearly as consistent on a station-by-station basis. For example, station SI was most contaminated with trace metals and had modified infauna but was not toxic to amphipods. Two adjacent stations, LI and A6, were only slightly contaminated and had modified infauna, but only A6 was toxic to amphipods. Station 09031 had very high levels of organic contaminants (slightly higher than those of station 10038). Most of the bioassays were positive at both stations, however, the percent contribution of the polychaetes and molluscs was lower at station 09031 than at station 10038. Stations A6, A10, 08004, 08005, 09027 and 09033 had highly modified infauna, but relatively low levels of the contaminants that were measured.

Station 10031 had a Bioassay Summary Index value equal to that of station 09031 and the collective stations 1406/1512/1606/1612, but the estimated concentration of organic chemicals at 10031 was about one-fourth that of the latter stations. Also, stations CII and HI had Bioassay Summary index values higher than that of station 10038, yet the concentration of organic chemicals was about one-third that of the latter station.

Compatibility of Data Sets

The good overall correspondence among measures is apparent despite several potential weaknesses in the data sets we reviewed. First, four laboratories performed the chemical analyses; no specific intercalibration exercises were performed to assure compatibility of the data. Each of the laboratories did not quantify the same analytes or use the same limits of detection. However, each has considerable experience with these analyses in Puget Sound and each has routinely employed a variety of quality assurance techniques, including analyses of standard materials. Three laboratories performed amphipod bioassays. All three recently (1984) participated in an interlaboratory comparison experiment using Puget Sound sediments and sediments spiked with three doses of cadmium. The results were significantly comparable between laboratories for samples that were very toxic and for those that were not toxic (Alan J. Mearns, U.S. NOAA, personal communication).

Second, data reviewed here were from studies in which sampling was performed in 1979/80, 1981 and 1983. Significant changes in sediment contamination have been demonstrated through analyses of age dated cores over 20- to 30-year time scales in the early to mid-1900s in Puget Sound. However, major changes over the more recent 4 year period of 1979 to 1983 are not apparent for the majority of toxicants (Crecelius & Bloom, in press). The data reviewed here reflect conditions in the upper 6 cm of sediments, thus they reflect contaminant accumulations over the previous 5–10 years.

Third, the triad of analyses were not always performed on the same samples. The sampling in Commencement Bay for the infauna, bioassay and chemical analyses performed by EPA was conducted during one time period (1981) as was that for Seattle METRO (1983). However, bioassays were performed on samples collected in 1983 (Samish Bay and Case Inlet) and 1981 (all others) at stations previously sampled for chemical and infauna analyses by NMFS in 1979 and 1980. The latter data set may suffer from the degree of patchiness observed by Swartz *et al.* (1982) in the waterways of Commencement Bay. However, the sampling in 1981 was conducted with extreme care to ensure that the samples were taken as near as possible to the stations used in 1979/80. In addition, numerous other studies (e.g. Malins *et al.*, 1984) have documented that the sediments of the urban bays of Puget Sound are clearly more contaminated than those from rural bays and the main basin of the Sound.

Finally, data from relatively few stations in reference areas met our criteria and were available; thus the data sets we reviewed were heavily skewed to highly contaminated parts of the region. The station in Case Inlet was tested with only one bioassay type. An unusually sandy station in Samish Bay was retained for our analyses to increase our number of reference stations from two to three. Sophisticated statistical treatments are precluded by this uneven distribution in the data. However, based upon unpublished single-parameter data reviewed by the authors, we are confident that Samish Bay and Case Inlet are representative of uncontaminated conditions in Puget Sound.

Conclusions and Recommendations

The term 'marine pollution' is generally used to indicate a biologically damaging excess. Marine pollution assessments, then, must encompass some biological test along with the usual chemical tests. McIntyre (1984), Chapman & Long (1983) and GESAMP (1980) have advocated the increased use of biological effects measures as integrated parts of pollution assessments. GESAMP (1980) concluded that: "Finally, without observations linking levels (of pollutants) in the water or sediment with tissue concentrations and then with effects on organisms and populations and, ultimately, with the well-being of the ecosystem as a whole, an adequate assessment of pollution is impossible." They observed that biological criteria are too often introduced in the evaluation stage of assessments, not as a routine procedure conducted simultaneously with the ubiquitous chemical analyses.

The chemistry data alone only provide measures of contamination. Concurrent biological data are needed to measure pollution. Based upon average conditions (Table 5) it would appear that the chemistry data would be a sufficient indicator of predictable biologic effects. However, on a station-by-station basis this predictability is thus far unattained. One cannot conclude much about biological consequences or significance of sediment chemistry data without concurrent biological measures. This lack of predictability is due to at least two factors: (1) the relatively narrow chemical window we can quantify compared to what is likely in the sediments; and (2) the highly variable and unmeasured degree of availability of sediment-bound chemicals. Similar observations were made by Tsai *et al.* (1979) in Baltimore Harbour. Sediment samples that appeared to be, overall, the most contaminated were also most toxic to fish in bioassays. However, no single chemical component among those they measured could be used as an indicator of sediment toxicity. The rank order of sites according to toxicity did not agree with that for all individual chemicals. However, they observed good correspondence between toxicity to fish and depressed species diversity index values for benthos.

Measures of resident community structure alone are also not sufficient to determine contaminant effects. The presence or absence of particular biota may be due to toxic chemicals, to fluctuations in environmental factors (e.g. temperature, salinity, dissolved oxygen); subtle variations in sediment texture or depth; or biologic factors such as recruitment cycles, predation and competition. Carriker *et al.* (1982) reviewed these and some of the other problems that ecologists face in attempting to interpret data on community structure relative to sediment contamination in the New York Bight.

We (Chapman & Long, 1983) advocated use of sediment bioassays as a part of a comprehensive approach to marine pollution assessments to help answer the biological 'So what?' question. Bioassays provide a direct test of toxicity (lethality or sublethal responses) of environmental samples. Until sediment bioassays are more broadly tested and applied, community structure data are, at least initially, needed to verify the significance of the laboratory-derived sediment bioassay results. Once the technology and significance of sediment bioassays are established, we advocate phasing out the infaunal portion of the Triad since infaunal taxonomic analyses can be relatively expensive. If perfect correspondence between bioassay and chemistry data is attained, one of these portions of the Triad could ultimately be phased out also. A full field trial of the Triad is needed to help establish this correspondence, where the samples would be collected synoptically, the analyses performed by one laboratory and the sample sizes equivalent in both contaminated and pristine sites.

The Sediment Quality Triad advocated here encompasses measures of sediment contamination, toxicity and resident infauna. We have presented the chemical data as sums of three selected trace metals and sums of selected organics, including PCBs. Chemical analytes should be those that are of particular concern in each project region, based on suspected or actual sources. We have presented bioassay data for the six types of tests performed at the 23 stations we used. Numerous other tests can be applied to the Triad depending upon locally-available expertise and assessment objectives. For example, bioassays with marine sediments can be performed with nematodes, copepods, sea urchin larvae, polychaetes, bivalves, mysids, bacteria, fish and shrimp—in addition to the organisms reported above. Amphipods, ostracods, insects, nematodes and fish can be used in tests with freshwater sediments. Where possible, bioassays should be performed with sensitivie, indigenous species so the results can be directly related to the infauna, as was done herein for the phoxocephalid amphipod, *R. abronius.* Also, tests with two or three species are optimal to ensure a comprehensive data set, especially for areas with moderate contamination that may be near the toxicity threshold for some species. We have elected to present the infauna data as percent contribution of selected taxonomic groups to total abundance. Benthic data can be expressed in a variety of ways, including: biomass, total abundance, species richness, diversity or taxa/taxa ratios.

The Sediment Quality Triad can best be applied to regional assessments of pollution conditions where the objective is to identify high, mid- and low priority areas for remedial action. The Triad can also be used in long-term monitoring programmes, in assessments of prospective marine dredge spoils for suitability for open-water disposal and in pre-construction siting studies of wastewater facilities. Using this approach, decisions regarding unreasonable or unacceptable degrees of pollution can be made based upon the preponderance of chemical, toxicity and biological data.

In the Puget Sound region, US EPA and the State of Washington have begun major research and planning activities in the waterways of Commencement Bay (a 'Superfund' site), along inner Elliott Bay, the lower Duwamish Waterway and other urban areas in preparation for remedial actions. These areas have been designated as high priority based upon, in part, results of sediment chemical, bioassay, and infauna analyses. In these management applications, all of the elements of the Sediment Quality Triad are proving to be useful and effective methods for determining sediment quality. In addition, interim dredged material guidelines for suitability for open-water disposal have been adopted by EPA and the State that are based upon sediment chemistry and bioassay analyses.

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